Development of HOM-damped cavities at BNL

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BNL

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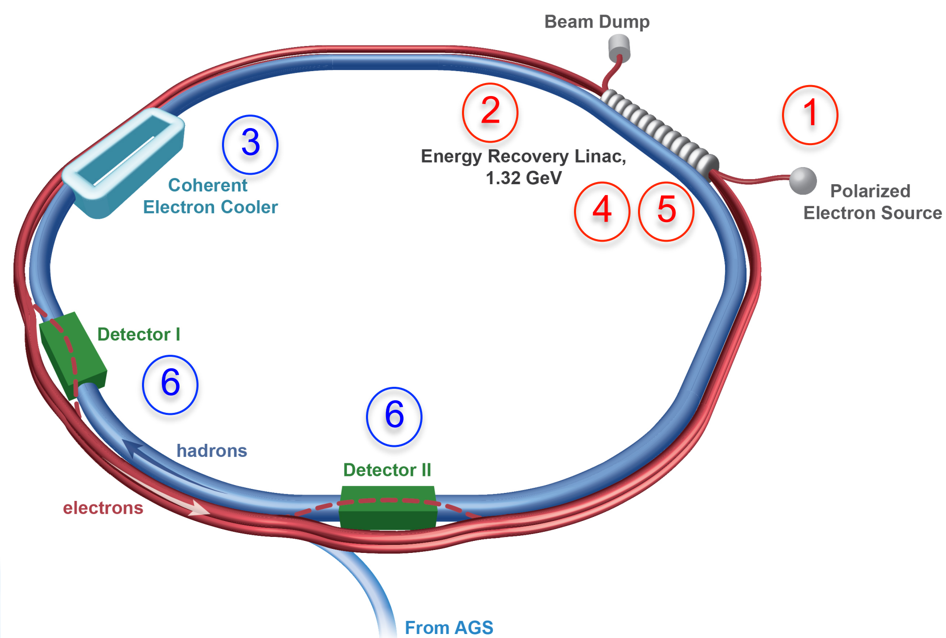
Introduction

- In this talk I will describe current efforts at BNL to develop HOM-damped superconducting RF cavities for eRHIC.
- These cavities might be of interest for future circular colliders such as CEPC and SPPC.

SRF systems of the FFAG eRHIC

An electron-ion collider eRHIC will collide high-intensity hadron beams from RHIC with an electron beam delivered by a multi-pass ERL. An FFAG-based ERL will accelerate an electron beam to 15.9 GeV after 12 passes through an SRF linac or to 21.2 GeV after 16 passes. In both cases, the linac energy is 1.322 GeV.



FFAG eRHIC will have the following SRF systems:

① 12 MeV ERL injection system.

② Main 1.32 GeV SRF linac, operating at 422 MHz. The final ERL energy is 15.9 GeV with 12 passes and 21.2 GeV with 16 passes.

③ An SRF ERL for Coherent electron Cooling (CeC) of the hadron beam.

④ 844 MHz (second harmonic) SRF linac for energy loss compensation.

⑤ 5^{th} harmonic SRF linac for energy spread compensation.

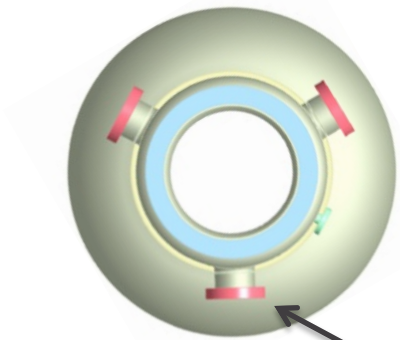
⑥ SRF crab cavities for hadrons and electrons around detectors. The former system will include 2^{nd} and 3^{rd} harmonics cavities for linearization.

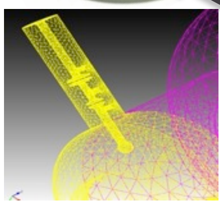
HOM-damped cavities for eRHIC

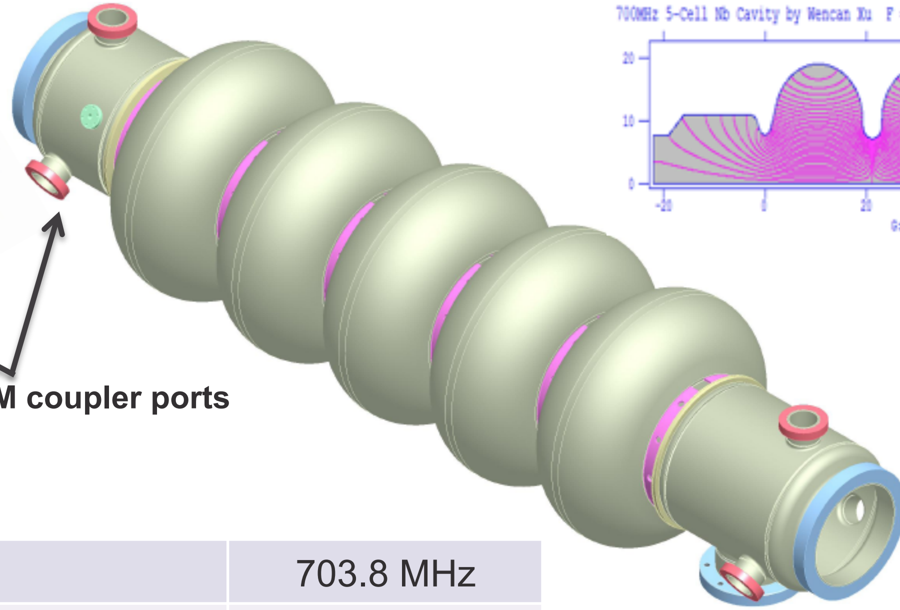
- To deal with ampere-class beam current in the ERL, all SRF cavities have to be HOM-damped. This includes main linac (422 MHz), second harmonic (845 MHz) cavities for energy loss compensation, fifth harmonic (2.1 GHz) system for linearizing energy spread, and crab cavities.
- In this presentation I will talk about the main linac cavities only.
- Here are parameters of the main ERL linac:

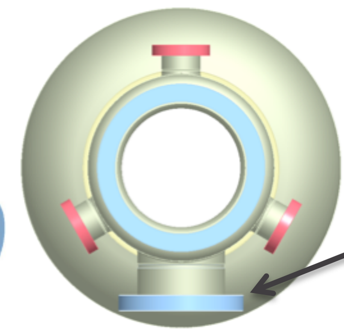
Linac energy gain	1.32 GeV
Number of passes	up to 16
Bunch repetition frequency	9.38 MHz
RF frequency	422 MHz
Number of SRF cavities	40
Linac fill factor	0.6
Accelerating gradient	18.5 MV/m
Operating temperature	1.9 K
Cavity Q at operating gradient	5×10^{10}
HOM power per cavity	1 kW

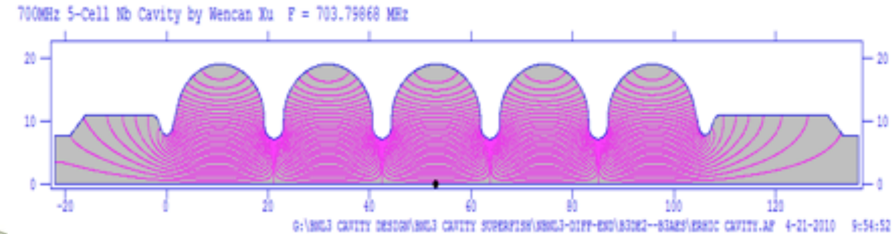
Five-cell cavity with strong HOM damping









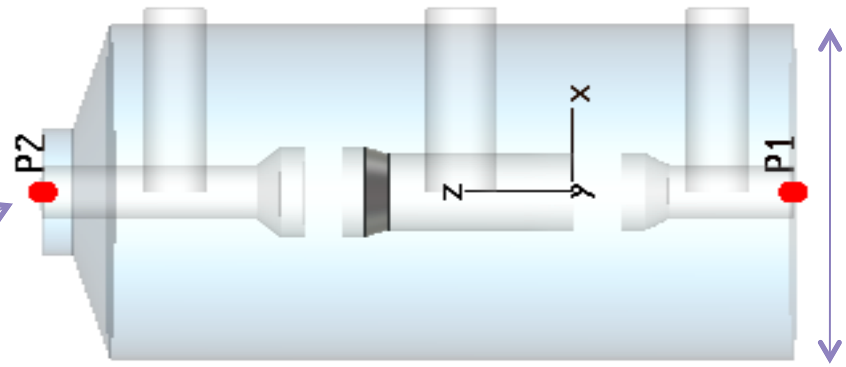


Frequency	703.8 MHz
R/Q	506.3 Ohm
Geometry factor	283 Ohm
Number of cells	5
Flange-to-flange length	1.58 m
Beam pipe radius	0.11 m
Q	4×10^{10}
E_{pk}/E_{acc}	2.46
B_{pk}/E_{acc} [mT/MV/m]	4.26 mT/(MV/m)
Lorentz force detuning	0.45 Hz/(MV/m)^2
Loss factor for 2 mm bunch length	3.96 V/pC

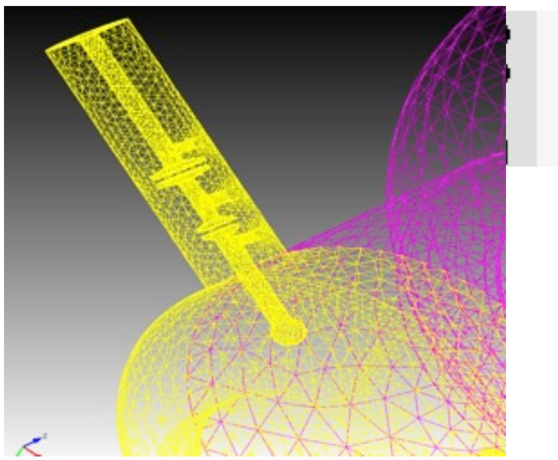
- The original design of eRHIC used RF frequency of 704 MHz. A five-cell SRF cavity (BNL3) has been developed at BNL before the eRHIC RF frequency was changed to 422 MHz.
- A prototype cavity reached 19.7 MV/m.
- Six antenna-type couplers will be attached to the large diameter beam pipes and will provide strong HOM damping while maintaining good fill factor for the linac.
- *Two HOM filters are currently under consideration: a high pass filter made of lumped elements and a dual-ridge waveguide filter.*

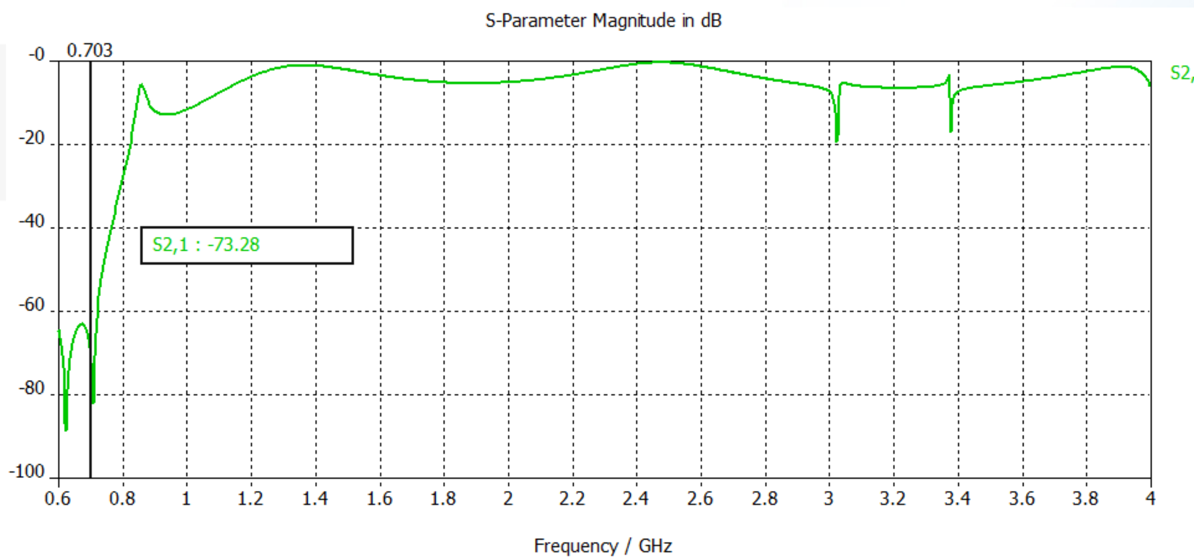
2-stage filter HOM coupler

50-Ohm transmission
line to room temperature
RF load



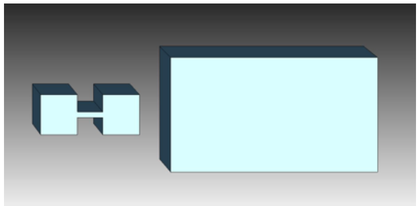
D = 72 mm

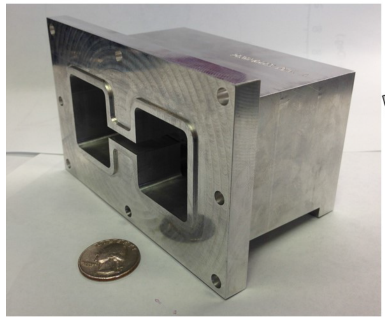


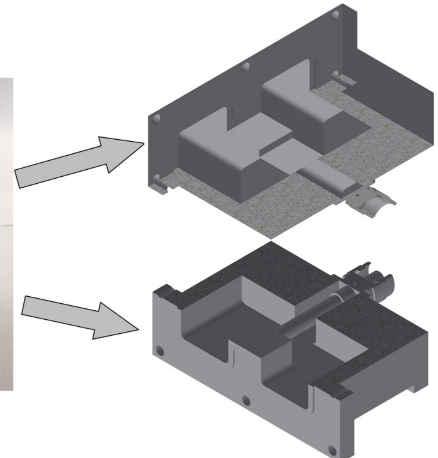


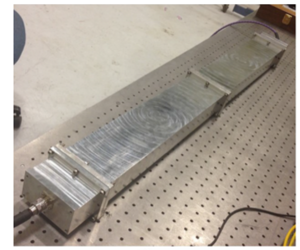
- Between the two notches, S21 < -65 dB, 1st HOM is at 0.82 GHz, S21 = -23 dB.
- It has good damping at high frequencies.
- Work on filter optimization continues.

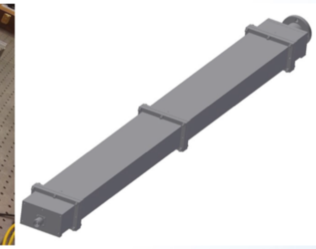
Dual-ridge waveguide HOM coupler

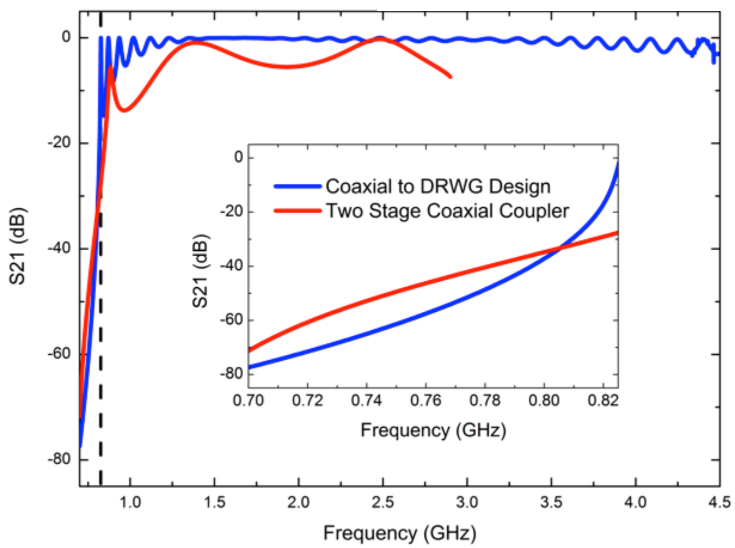


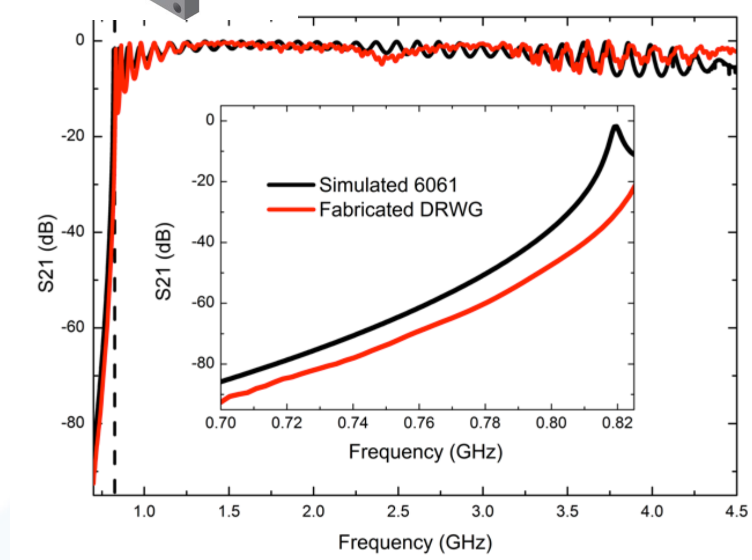












- More compact than rectangular waveguide.
- A very broadband coax-to-waveguide transition was developed.
- Better transmission than that of the 2-stage coaxial coupler.

Considerations for the main linac frequency choice

The following considerations affect the frequency choice for the main ERL linac:

- Bunched beam structure.
- Bunch length and energy spread.
- BBU threshold.
- SRF losses
- RF power efficiency.
- Cost and complexity.

For the FFAG eRHIC ERL, most of these considerations point toward lower frequency.

Details can be found in our paper presented at IPAC'2014

Proceedings of IPAC2014, Dresden, Germany TUPME084

ON THE FREQUENCY CHOICE FOR THE eRHIC SRF LINAC*

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Dipole HOMs and BBU threshold

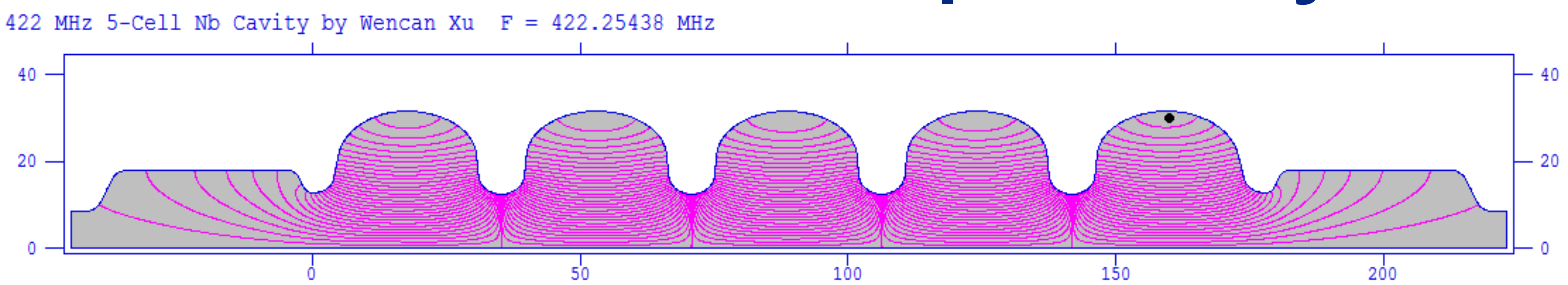
- Transverse beam break up (BBU) is the dominant effect limiting beam current in ERLs. The instability threshold current is inversely proportional to the frequencies of higher order modes (HOMs):

$$I_{th} \propto \frac{1}{\omega_d \left(R/Q\right)_d Q_{L,d} M_{12}}$$

, here R/Q has units of Ohm and is independent on frequency.

- Also, the number of HOMs is reduced, as fewer low-frequency cavities are required to build the linac.
- This consideration is of a special importance for a multi-pass ERL.

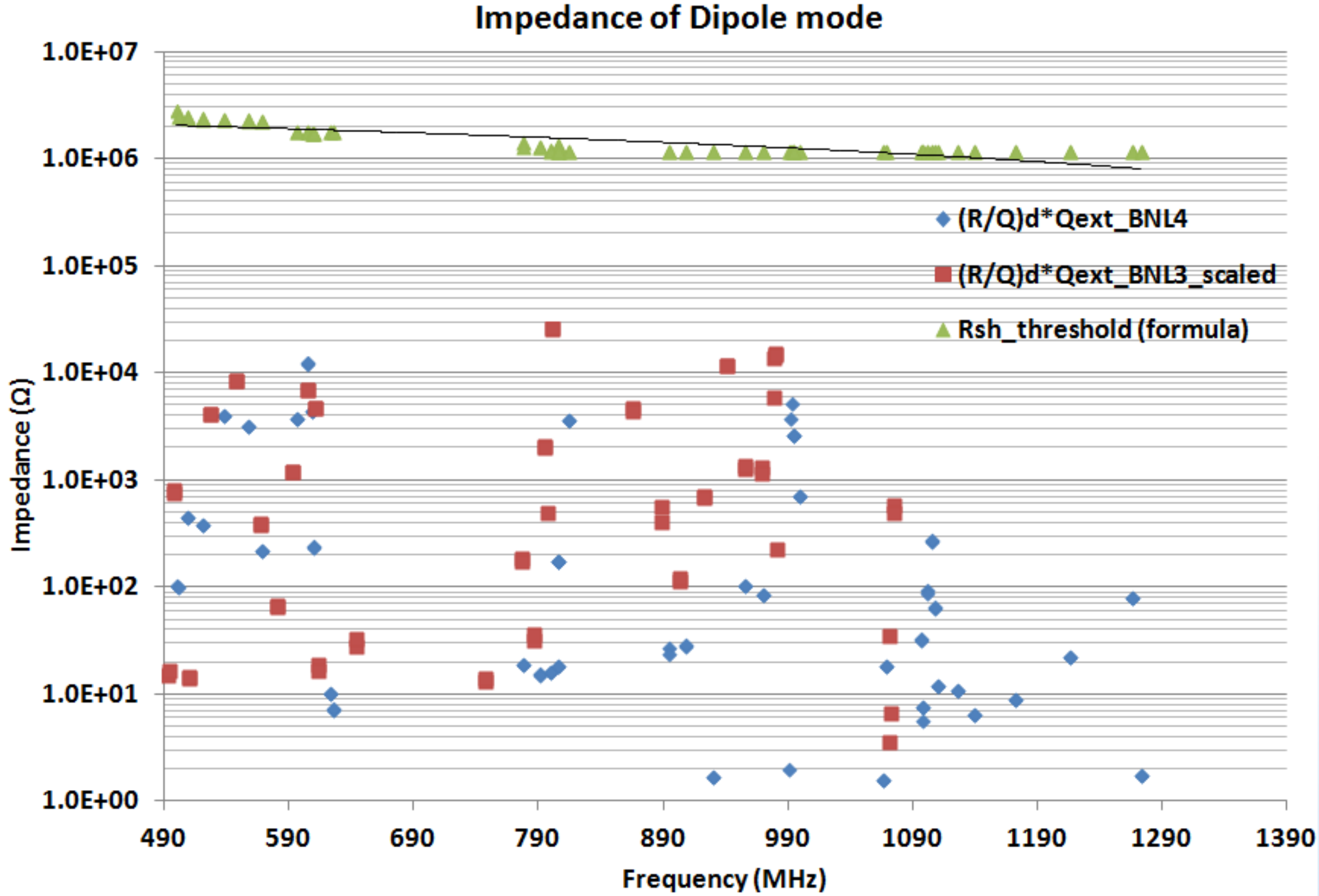
422 MHz HOM-damped cavity



- R&D on the 422 MHz BNL4 cavity is in progress (BNL's LDRD).
- The RF design is complete with the cavity shape re-optimized from the scaled 704-MHz BNL3 cavity model:
  - The first HOM of the BNL4 cavity is 15 MHz further away from the fundamental mode.
  - The BNL4 cavity's has higher transverse and longitudinal BBU threshold than the scaled BNL3 cavity.
  - The HOM power for BNL4 is 10% lower than for the scaled BNL3 cavity.

Parameters	BNL3_scale	BNL 4
Frequency [MHZ]	422	422.2
beta	1	1
Cells No.	5	5
Geometry Factor	283	273
(R/Q)/cell [Ω/cell]	101	100.6
Epeak/Eacc	2.46	2.27
Bpeak/Eacc [mT/MV/m]	4.26	4.42
Coupling factor [%]	3.02	2.83
Length with HOM damper (cm)	267	270*
Beam pipe radius (mm)	183	180
Radius after tapered (mm)	83	85
First HOM frequency (MHz)	483	498

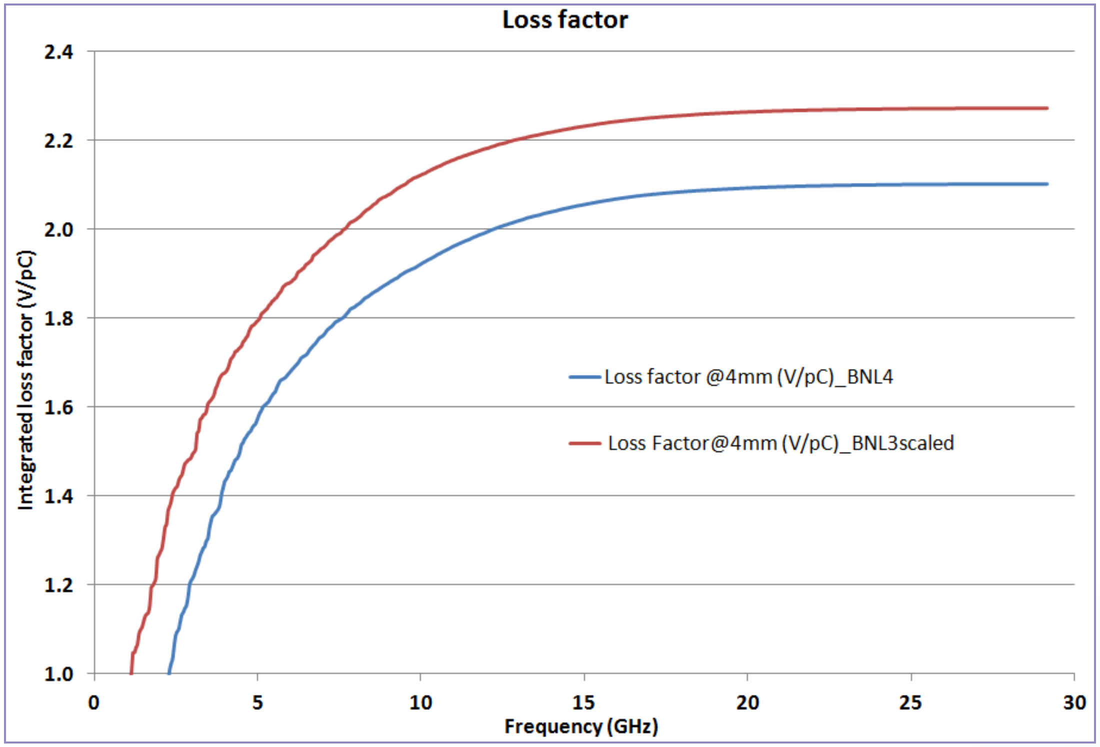
Transverse BBU threshold



Notes:

- Beam parameters: 18 mA 16-pass ERL, M_{12}= 150 m;
- The threshold impedance is divided by N^2 = 256 for 16 passes;
- Very conservative beam parameters are used in threshold estimation.

HOM power at high frequencies

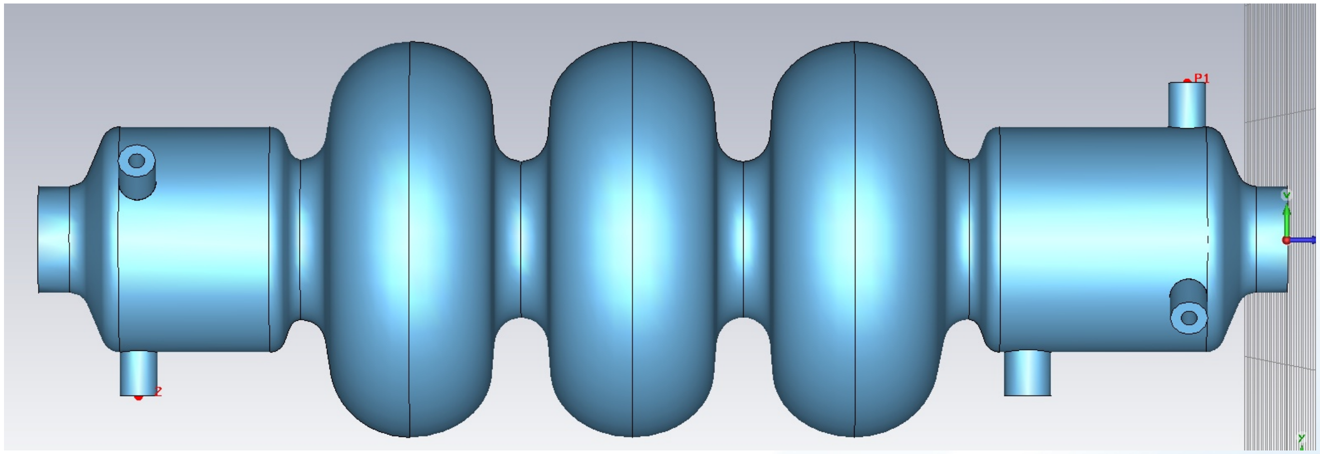


$$P_{\|} = k_{\|} Q_{bunch} I_{beam}$$

- While HOM couplers are good for damping low-frequency HOMs, they are not very efficient in dealing with high-frequency part of the HOM spectrum.
- About 30% of the HOM power will be generated above 5 GHz.
- To prevent this power from dissipating in cavities, it will have to be either absorbed in beam pipe absorbers or couplers out via special beam pipw HOM couplers.
- We are investigating both options.

422 MHz HOM-damped cavity

- A 3-cell prototype cavity will be ordered in the near future to validate the design and study different treatment options.

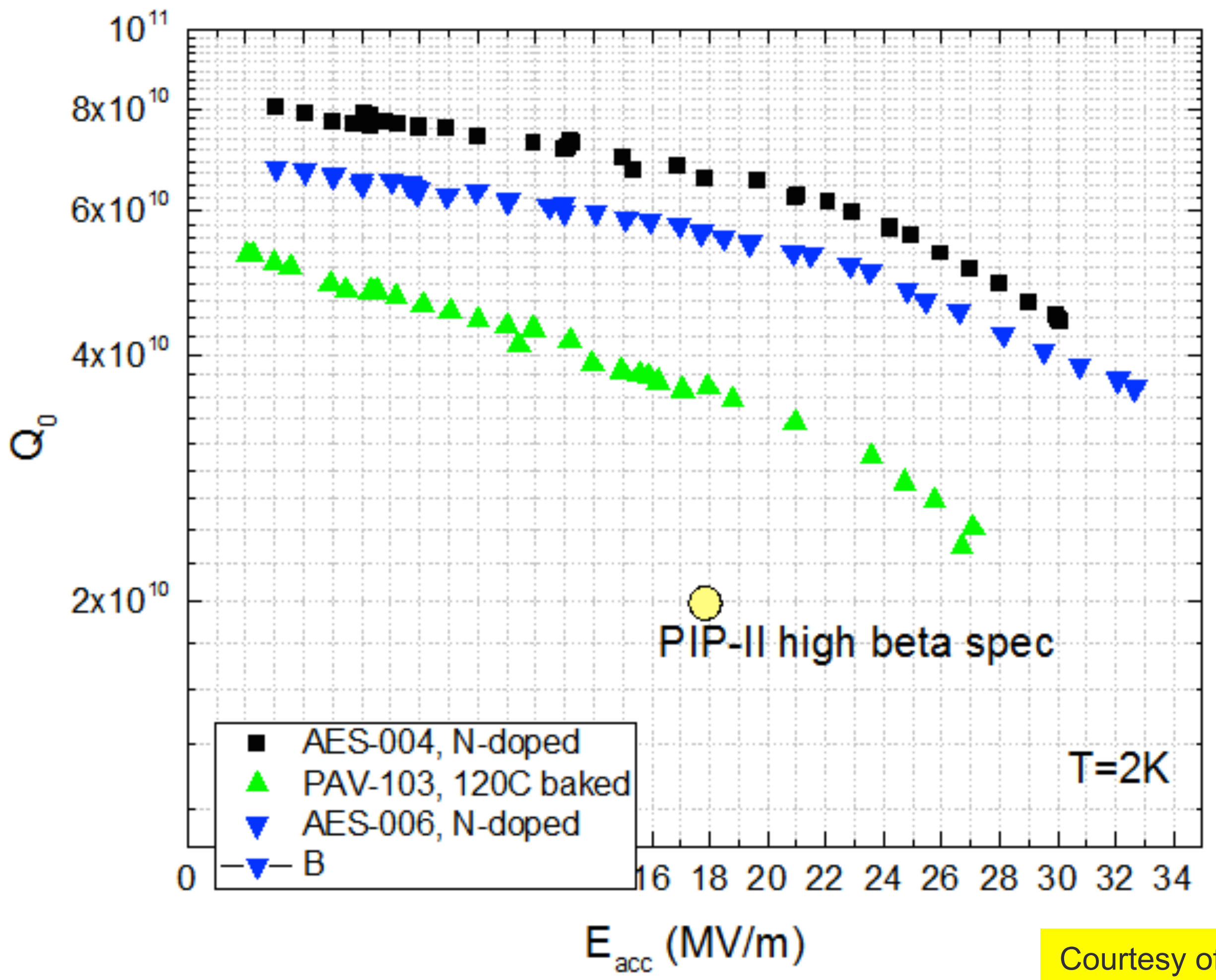


Nitrogen doping for low frequency SRF cavities

- Recent R&D efforts at Fermilab led to discovery of nitrogen doping treatment, which results in record low BCS surface resistance, reduced non-flux residual resistance.
- Thanks to LCLS-II at SLAC, nitrogen doping has received a strong technological push to make it production-ready at 1.3 GHz 9-cell cavities. This was accomplished by collaborative efforts at Fermilab, Cornell and JLab.
- Initial results from applying nitrogen doping to lower frequency (650 MHz) cavities st Fermilab are very promising.
- At BNL, we are initiating a collaboration with JLab to study nitrogen doping on a single cell 400 MHz cavity.
- If this research is successful, we plan to apply the recipe to eRHIC SRF cavities. It will result in significant capital and operational cost savings.

Nitrogen doping of 650 MHz cavities – first results

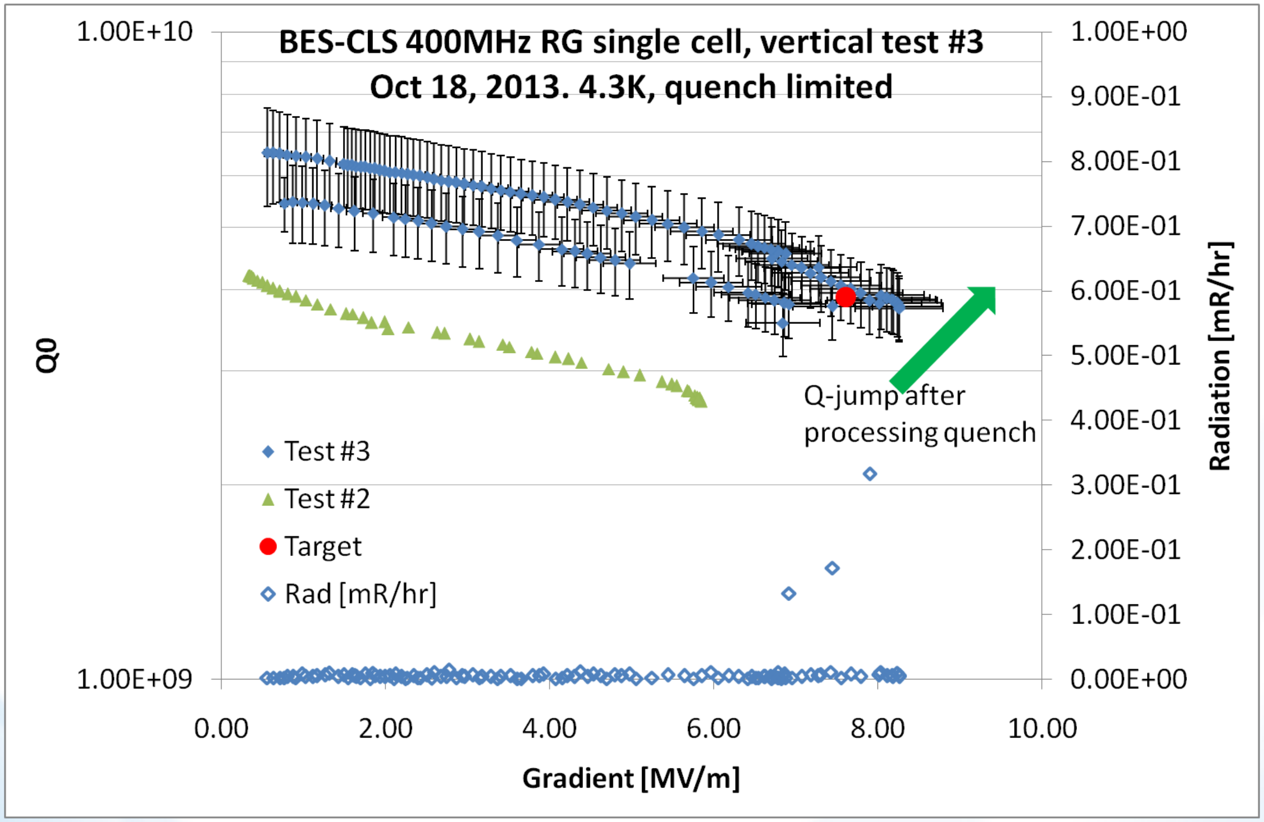
Applying N doping to 650 MHz (β = 0.9) leads to double Q compared to 120°C bake (standard surface treatment ILC/XFEL), ~7×10^{10} at 2 K – world record at this frequency



Courtesy of A. Grasselino (Fermilab)

400 MHz single cell cavity

- A 400 MHz single cell cavity was fabricated and tested at JLab.
- We plan to bring this cavity to BNL, re-test and apply nitrogen doping.



Courtesy of R. Rimmer (JLab)

Summary

- BNL is working on a future electron-ion collider eRHIC.
- Such a collider will require HOM-damped SRF accelerating cavities operating at several RF frequencies.
- We have developed a 5-cell HOM-damped structures for the main linac of eRHIC. A prototype 704-MHz BNL3 cavity has reached an accelerating gradient close to 20 MV/m.
- Two HOM coupler schemes are under consideration: a 2-stage coaxial filter and a dual-ridge waveguide filter. To deal with high-frequency part of the HOM spectrum, we are investigating beam pipe absorbers and couplers.
- A 422 MHz cavity was designed and its prototype will be ordered in the near future.
- A study of nitrogen doping for low frequency cavities has been initiated in collaboration with JLab. If a successful recipe is found, this treatment will be applied to eRHIC cavities. It will offer both capital and operational cost savings.
- We are open for collaboration with other laboratories.

Acknowledgements

I. Ben-Zvi, Wencan Xu, C. Marques (M.S. 2014, SBU), …

Thank you!